High-yield neutron activation system for the National Ignition Facility

Cris W. Barnes,[a] Thomas J. Murphy, and John A. Oertel
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

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The most accurate absolutely calibrated measurement of the total yield of neutrons from experiments on the National Ignition Facility will be from activation of threshold nuclear reactions. The high-yield neutron activation system is being designed to provide high-accuracy (similar to the $\pm 7\%$ achieved on other fusion experiments) linear measurements over a 9-order-of-magnitude dynamic range from the facility limit of $\sim 10^{19}$ neutrons/shot down to a minimum of $\sim 3 \times 10^{10}$ neutrons/shot. The system design requirements are presented, and a conceptual design to meet those requirements described. [DOI: 10.1063/1.1319360]

I. INTRODUCTION

The total fusion energy production from inertial confinement fusion targets at the National Ignition Facility (NIF) will be measured by a variety of fusion product diagnostics. Possibly the most accurate and precise determination of the total neutron yield over extreme dynamic range comes from radioactivity produced by threshold nuclear reactions in small samples placed near the target and then subsequently removed to count the gamma-ray activation. Such techniques have achieved $\pm 7\%$ (one-sigma) accuracy on magnetic fusion devices such as the Tokamak Fusion Test Reactor (TFTR)[1] and the Joint European Torus (JET), and have demonstrated dynamic range between shots while maintaining this accuracy of over six orders of magnitude.[2]

The high-yield system for NIF uses thin elemental samples (''foils'') for which the gamma-ray detection efficiency can be calculated accurately from first principles. Then using dosimetric cross sections and standard nuclear physics parameters, the measured fluence can be determined and turned into total yield using neutronics modeling of the target chamber. Such a system can work down to 10^6 neutrons/cm^2 which, assuming a 50 cm ''exclusion radius'' or minimum distance to the laser-driven target, means minimum yields of 3×10^{10} neutrons/shot. By increasing the sample distance to near the target chamber wall (4 m), reducing the sample mass, and increasing the counting rate, yields up to the maximum allowable on the system can be measured. A complementary low-yield activation system[3] will use larger masses to achieve higher sensitivity and will use associated particle methods[4] at an accelerator to determine the calibration.

In this article the system design requirements will be detailed for the high-yield neutron activation system on NIF. A pneumatic transport system similar to that used on TFTR and designed for the International Thermonuclear Experimental Reactor (ITER)[5] will be described as well as the requirements for the ''irradiation ends'' or reentrant equipment used to position the samples for activation and also the counting system. After this Introduction, Sec. II describes the design requirements the system should meet, and Sec. III presents the initial conceptual design to meet those requirements.

II. SYSTEM DESIGN REQUIREMENTS

The neutron yield activation system shall be deployed for all neutron producing experiments and be used to measure the total neutron yield of a shot above various thresholds set by the activation reactions.

The absolute calibration of the high-yield neutron activation system for NIF will come from a ''first principles'' approach using dosimetric cross sections, known nuclear data,[6] absolutely calibrated analytical balances and gamma-ray sources, and calculations of gamma-ray efficiency of detection to ''thin'' activated foils. The systematic correction from calculations of self-attenuation of gamma rays in the foils from the finite extent of the sources should be small to achieve high system accuracy. This limits the maximum size of the foils to be used to typically a few grams. Based on previous experience, the measurable fluence with small statistical counting error will be $\sim 10^6$ n/cm^2. (The low-yield system,[3] using accelerator-based associated particle techniques[4] and larger masses should work down to 10^5 n/cm^2 or lower.) Assuming an exclusion radius of 50 cm is allowed,[7] this allows measurements of minimum yields of $\sim 3 \times 10^{10}$ neutrons/shot.

The system must work up to 10^{19} neutrons per pulse which is over 20 MJ of fusion energy, the facility limit. This is a fluence of $\sim 10^{13}$ n/cm^2 when the sample is near the vacuum vessel wall. Thus, the system needs ~ 9 orders-of-magnitude dynamic range in the yield. At these high fluences, even small masses require remote handling to maintain ''as low as reasonably achievable'' (ALARA) radiation safety to personnel.

In deuterium–deuterium (DD) shots, one should be able to measure the deuterium/tritium (secondary) yield as well using threshold reactions. It is useful to be able to measure a variety of reactions for cross-calibration and error reduction[2] and to determine the neutron spectrum.[8]

(a) Samples: The same transport system will be used for both the low-yield and high-yield systems. Sample size of up

[a]Electronic mail:cbarnes@lanl.gov

to ten's of grams and liquid samples should be possible.

Operation and handling of radioactive material should follow ALARA requirements. Radioactive samples must be safely stored someplace. This should be close to the counting room for ALARA purposes, but not in that same room [the pneumatic switchyard room (see below) would be a good place].

(b) Irradiation ends: Reentrant irradiation ends extending well inside the vacuum vessel wall and close to the target are needed to provide a low-scattering environment for neutron activation measurements. At least two irradiation ends are needed (at roughly ''equivalent'' locations, that is similar polar angle θ but different azimuthal angle ϕ) for cross calibrations. Data from different azimuthal angles (representing pole, equator, and in between of implosion) should be taken, to look for possible (but unlikely) emission anisotropy and possible spectrum changes using threshold reactions sensitive to such changes. Such emission anisotropy is most likely to show up (if at all) between pole and equator of the hohlraum drive rather than at different ϕ angles. Thus we would like at least three (preferably four) irradiation ends on the vacuum vessel, one near the top or bottom (at the pole of the implosion), a couple on the equator (or near it), and one midway between the equator and the pole. Such irradiation locations spaced in θ would also be useful to look for neutron spectrum changes using threshold reactions. Each irradiation location should be able to be placed close ($\sim$50 cm) to target chamber center or at distances further out [4 m from target chamber center (TCC) or 1 m from wall might be maximum location].

(c) Gamma-ray detectors: We will want one high-energy-resolution counting system, preferably with very low background, and another counting system perhaps of high-efficiency (trading off energy resolution) also with very low background. Once high-resolution analysis of particular types of foils have confirmed no competing lines or background, simple low resolution but robust detectors can be used. Since multiple samples may be desired to be counted at once, two such simple robust systems may be needed. There needs to be at least one NIM crate (probably two).

(d) Computer control: All three (or more) counting systems should be controllable from a single workstation (connected to network). This workstation should also communicate with the pneumatic system control (see below) to help keep an audit trail of samples (what has been sent where when). Official system shot number and time (universal time accurate to 1 s) should be available as input to the computer. Diagnostic status (sample in place and ready) should be broadcast to system control (see standards for such systems[9]). Results (yields) should be available online within a day, with preliminary results available within 2 h.

(e) Pneumatic transfer system: There should be a pneumatic system to automatically return samples and minimize handling of radioactive material. Flexibility in routing capsules from different irradiation ends to different detectors is needed, both in operation and in adding future system components.

Activated air within the pneumatic system will have to be flushed. Some valves in the target bay can help with this,

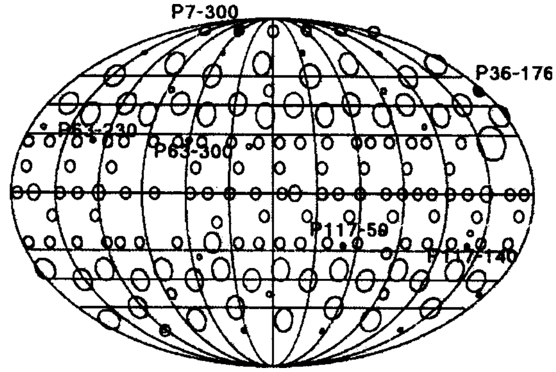

FIG. 1. Location on NIF of ports to be used for neutron activation. The ports are labeled with the polar angle and azimuthal angle on the NIF vessel, as in P36-176 being 36° from the top.

but any switchyard room (see below) may also need to be considered off limits during ignition operation.

III. CONCEPTUAL DESIGN TO MEET REQUIREMENTS

(a) Irradiation locations: While two irradiation locations at similar θ angles are needed for cross-calibration purposes, the position of the other two locations is questionable. While observing neutron emission anisotropy or even energy anisotropy is not highly likely on NIF, any such anisotropy is more likely to be seen between the pole and the equator. At present, ports P63-230, P63-300, P117-50, and P117-140 have been allocated for neutron activation irradiation ends, all at 63° angle from the poles. We would like access to an 8 in. outer diameter (o.d.) subflange of a P7 port, and to P36-176, but this will require iteration of the irradiation end design and other diagnostics near those locations. Figure 1 shows the proposed locations for neutron activation irradiation ends.

Activation by neutrons can provide a highly accurate determination of the neutron fluence through the elemental foils exposed to the fusion source. The desired measurement, however, is the total fusion energy from the yield of the inertial confinement fusion target. The ratio of energy-dependent fluence to total fusion yield will be calculated using a fully three-dimensional Monte Carlo calculation.[1] The calibration technique to be used by this system will allow inclusion of effects caused by any energy-dependent neutron spectra. These calculations allow the effects of neutron scattering from the device structure to be evaluated at different locations.

To achieve the desired 9-orders-of-magnitude dynamic range while maintaining linearity and high accuracy, several techniques will be used in parallel. Changing the radial location of the sample by moving the irradiation end can provide a factor of $(400/50)^2 = 64$. The sample mass can be changed from $\sim$5 g to 100 mg or another factor of 50. Decay for several half-lives is ineffective in operation and provides factors of a few at best. Similar factors of a few are available by choosing different materials with different dosimetric cross sections. Count rate at the detector can vary linearly about a factor of 10^4 between problems with background noise and high-count-rate pileup. The count duration and statistical er-

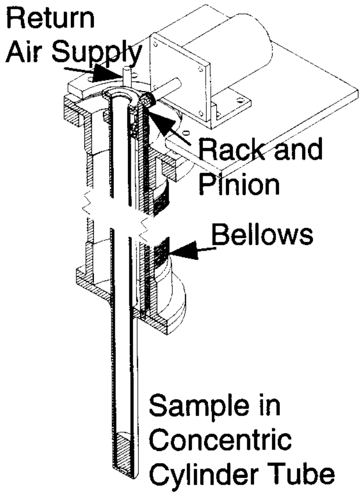

FIG. 2. Conceptual design of extendible irradiation end capable of positioning sample capsule from the vacuum vessel wall to within 50 cm of target chamber center. The irradiation end fits on a vacuum flange and points towards target chamber center.

ror accepted can also be varied to provide an additional factor of 10. Finally, if necessary, the distance of the sample to the detector can be increased to reduce the counting efficiency.

The expected dynamic range of the system can be illustrated by two examples. Using the $^{28}\mathrm{Si}(n,p)$ reaction, 5 g of pure silicon irradiated by total yield of 3×10^{10} neutrons at 0.5 m from the target and counted for 300 s (more than twice the 134 s half-life of the decay) with a 1% efficient detector would provide 150 counts. This number of counts could be increased with higher efficiency detection at the 1779 keV gamma-ray energy or by being closer to the target. At the full 10^{19} neutron yields, 100 mg of pure aluminum irradiated at 4 m and counted for 1000 s with a 1% efficient detector using the $^{27}\mathrm{Al}(n,\alpha)$ reaction would provide 1.3×10^5 counts or 130 cps which is not too high a count rate.

Figure 2 shows the initial design for an NIF neutron activation irradiation end. The positioner at the irradiation end will have bellows and encoded rack and pinion and be remotely controlled by the activation control system. The bellows, rack, etc. all fit on a 6 in. inner diameter (i.d.) flange. For a 3.5 m throw (from 4 to 0.5 m from TCC) we need that much space external to the vessel as well. The air supply and moving parts are all at atmosphere.

(b) Pneumatic transfer system: A ''carousel'' switch system that allows a sample capsule from any irradiation end to be routed to any detector, as implemented at JET, is the easiest and most flexible. This carousel switchyard/holding area will need to be a separate room from the counting/detector room for safety purposes. The computer control of the pneumatic system will require a computer/electronics rack.

The same 1 in. o.d. 2.5 in. long capsules used on TFTR (with 0.75 in. i.d. and 2 in. high central cavity) can thus hold up to 15 cm^3 which should be sufficient to handle the tens of grams of samples required for the most sensitive measurements. Further thought is needed about safety aspects using liquid samples. Some sort of double encapsulation will pos-

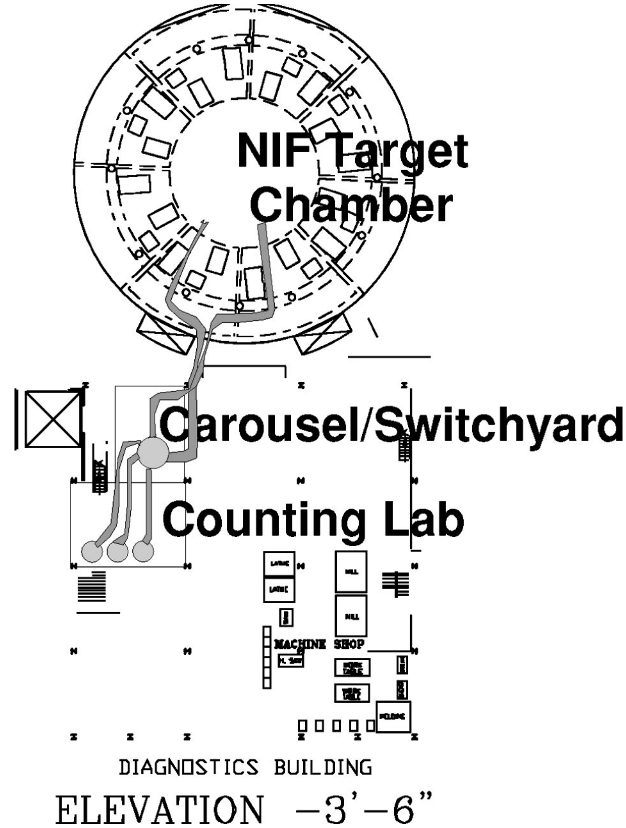

FIG. 3. Diagram showing possible routing of pneumatic transfer system from the NIF target chamber to the carousel switchyard room and then to the counting laboratory.

sibly be required as the single shell capsules can crack during use. Figure 3 shows a typical layout in a plan view of the NIF facility for how the pneumatic lines can get from the target chamber to the carousel room and thence to the counting room.

A critical issue in routing the pneumatic system is the minimum radius of curvature allowed and available. One can support[10] about a 10 in. radius of curvature for a 1 in. capsule in 1 1/8 in. i.d. tubes, as on TFTR.

Figure 4 shows a piping and instrumentation diagram for the pneumatic system. Such a layout allows for flexible op-

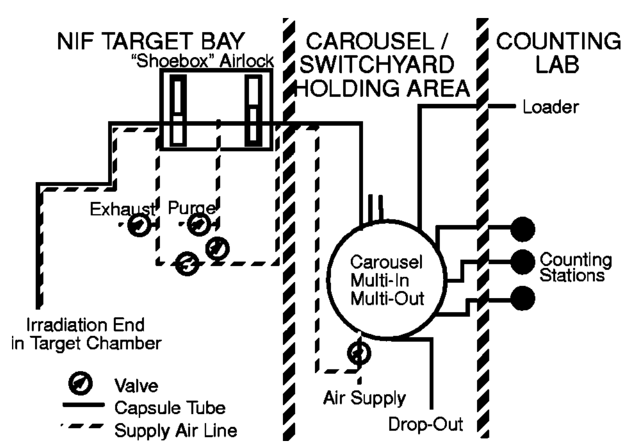

FIG. 4. Piping and instrumentation diagram for pneumatic transport system allowing capability of flushing activated air and providing flexible routing of capsules.

eration of the system, and safe flushing of activated air during high yield operation. We will plan to use compressed air as the propellant, as that is simplest and there is no need for any gas lower in activation or with better thermal conductivity.

Monitoring of capsule location and arrival is necessary to system operation. As in the ITER design[10] we plan to use plugging of the channel by the capsule and the resulting pressure change as a robust radiation-insensitive monitor of capsule arrival at the irradiation end. More usual electrical and optical techniques (such as fiber optic loops where the light is interrupted by passing samples) can be used at the airlocks and carousel and counting rooms where the radiation environment is not an issue. This requires fibers routed along pneumatic tubes and electronic equipment in diagnostic racks outside target bay that then communicate with computers in the counting room. For irradiation ends on the ''bottom'' of the vacuum vessel, samples will need to be kept in place either by continuously blowing air or some fail-safe latching mechanism (the first option works on JET and is fail safe itself).

(c) Detectors: The high-energy-resolution systems with low background would be high-purity germanium cryogenically cooled detectors in a shielded environment, one a well detector with high efficiency. Different materials tend to have different half-lives and can be effectively counted sequentially on the same detector, thus minimizing the need for multiple detectors when multiple activation samples are used. For the simple robust systems we propose using large NaI scintillators. An absolutely calibrated gamma-ray source is needed, and it must be replaced each year or two. Finally, a long half-life, weak source in a capsule is needed for routine monitoring of system stability.[5]

While good accuracy has been achieved with neutron activation systems, some design work is needed to try to improve precision or repeatability of measurements. Random perturbations of where the capsule with activated sample is with respect to either the detector or the fusion source can vary the system efficiency. This causes an imprecision beyond anything due to counting statistics which should be the limiting factor.

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